

The University of Bradford Institutional Repository

<http://bradscholars.brad.ac.uk>

This work is made available online in accordance with publisher policies. Please refer to the repository record for this item and our Policy Document available from the repository home page for further information.

To see the final version of this work please visit the publisher's website. Access to the published online version may require a subscription.

Link to publisher version: <https://doi.org/10.1016/j.cherd.2013.12.025>

Citation: Vera-Sorroche J, Kelly AL, Brown EC et al (2014) The effect of melt viscosity on thermal efficiency for single screw extrusion of HDPE. Chemical Engineering Research and Design. 92(11): 2404-2412.

Copyright statement: © 2016 The Authors. This is an Open Access article distributed under the [Creative Commons CC-BY license](#).





Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

IChemE

The effect of melt viscosity on thermal efficiency for single screw extrusion of HDPE[☆]



Javier Vera-Sorroche^{a,*}, Adrian L. Kelly^a, Elaine C. Brown^a,
Tim Gough^a, Chamil Abeykoon^a, Phil D. Coates^a, Jing Deng^b,
Kang Li^b, Eileen Harkin-Jones^c, Mark Price^c

^a IRC in Polymer Engineering, School of Engineering, Design & Technology, University of Bradford, BD7 1DP, UK

^b School of Electronics, Electrical Engineering and Computer Science, Queen's University, Belfast BT9 5AH, UK

^c School of Mechanical & Aerospace Engineering, Queen's University, Belfast, BT9 5AH, UK

ABSTRACT

In this work, a highly instrumented single screw extruder has been used to study the effect of polymer rheology on the thermal efficiency of the extrusion process. Three different molecular weight grades of high density polyethylene (HDPE) were extruded at a range of conditions. Three geometries of extruder screws were used at several set temperatures and screw rotation speeds. The extruder was equipped with real-time quantification of energy consumption; thermal dynamics of the process were examined using thermocouple grid sensors at the entrance to the die. Results showed that polymer rheology had a significant effect on process energy consumption and thermal homogeneity of the melt. Highest specific energy consumption and poorest homogeneity was observed for the highest viscosity grade of HDPE. Extruder screw geometry, set extrusion temperature and screw rotation speed were also found to have a direct effect on energy consumption and melt consistency. In particular, specific energy consumption was lower using a barrier flighted screw compared to single flighted screws at the same set conditions. These results highlight the complex nature of extrusion thermal dynamics and provide evidence that rheological properties of the polymer can significantly influence the thermal efficiency of the process.

© 2014 The Authors. Published by Elsevier B.V. All rights reserved.

Keywords: Polymer extrusion; Melt temperature; Energy; Rheology

1. Introduction

Consumption of polymeric materials has greatly increased over the past few decades due to their use in diverse industrial sectors. Plastics are in high demand in the packaging, construction, automotive, electrical and electronics industries, in addition to many other diverse applications. European plastics demand totalled 47 million tonnes in 2011, 21% of the total world production and generated an estimated annual turnover of 300 billion Euros, employing 1.45 million European citizens.

Polyethylene represented 29% of the total plastics demand (5.64 million tonnes of HDPE) (Plastic – the Facts, 2012).

In polymer processing machinery such as single screw extruders, polymer feedstock is fed into the machine through a hopper, conveyed along the screw and melted by a combination of applied external heat and internal shear heat generation. The pressure generated forces the molten material through a shaped die to form the final product. The quality of the extruded product is highly dependent upon the consistency of melt produced by the screw. Screw design needs

[☆] This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution and reproduction in any medium, provided the original author and source are credited.

* Corresponding author. Tel.: +34 620239697.

E-mail addresses: J.VeraSorroche@student.bradford.ac.uk (J. Vera-Sorroche), A.L.Kelly@bradford.ac.uk (A.L. Kelly), E.Brown@bradford.ac.uk (E.C. Brown), T.Gough@bradford.ac.uk (T. Gough), Y.Abeykoon@bradford.ac.uk (C. Abeykoon), P.D.Coates@bradford.ac.uk (P.D. Coates), JDeng01@qub.ac.uk (J. Deng), K.Li@qub.ac.uk (K. Li), E.Harkinjones@qub.ac.uk (E. Harkin-Jones), M.Price@qub.ac.uk (M. Price).

Received 11 September 2013; Received in revised form 9 December 2013; Accepted 16 December 2013

Available online 29 December 2013

0263-8762/\$ – see front matter © 2014 The Authors. Published by Elsevier B.V. All rights reserved.

<http://dx.doi.org/10.1016/j.cherd.2013.12.025>

Table 1 – Molecular weight characteristics for three grades of HDPE.

	Mw	Mw/Mn (MWD)	MFI (g/10 min) (2.16 kg load, 190 °C)
HD5050EA	91,727	4.1	3.81
HD6007S	119,000	5.8	0.62
HM5411EA	256,000	15	0.14

to be matched to polymer type in order to minimise melting instabilities and pressure inconsistencies and to optimise pumping consistency through the die (Steward, 2002; Lee and Wheeler, 1991; Rauwendael, 1990). Optimised screw geometry can lead to better thermal homogeneity and increased output and final product quality with lower energy usage. It has been shown that extruder heaters consume less energy when the extruders are operated at higher screw speeds (Cantor, 2010). It has also been found that single screw extruders should be operated at the highest screw speeds to maximise efficiency, whilst the screw geometry should be carefully chosen to optimise melt temperature (Vera-Sorroche et al., 2012; Kelly et al., 2012).

Polyethylenes are semi-crystalline thermoplastics that exhibit non-Newtonian pseudoplastic behaviour in the molten state. The relationship between molecular weight, its distribution and rheology plays an important role and hence should be investigated when examining polymer processability in single screw extrusion (Agassant and Villemaire, 1998; Hoffman and McKinley, 1985; Krishnaswamy and Rohlfing, 2004; Craig et al., 1968). The aim of this work was to study the effect of HDPE rheology on melt quality and energy consumption in single screw extrusion using real-time measurement techniques. Thermocouple grid sensors enabled characterisation of the thermal dynamics of the extrusion process which in combination with real-time energy consumption measurements facilitated an understanding of the thermal efficiency of the process (Brown et al., 2004; Abeykoon et al., 2012). The role of processing conditions, extruder screw geometry and set extrusion temperatures was examined, and the effect of rheology on measured melt temperatures and energy consumption was quantified, in order to highlight potential energy savings from careful selection of processing conditions and screw geometry.

2. Materials

Three different molecular weight grades of high density polyethylene (HDPE) were used throughout the studies. The first material was a high density copolymer (Rigidex HD5050 EA, Ineos) with a narrow molecular weight distribution for use in injection and compression moulding applications where high environmental stress cracking resistance is required. The second resin was a medium molecular weight homopolymer polyethylene (Rigidex HD6007S, Ineos) designed for blow moulding and extrusion applications. The third material was a high molecular weight copolymer grade (Rigidex HM5411EA, Ineos) supplied for medium and large blow moulding applications requiring high environmental stress cracking resistance and good rigidity. The nominal molecular weight characteristics of the three polymers are presented in Table 1.

Table 2 – Extruder set temperatures for all grades of HDPE and 3 screw geometries.

	Zone 1	Zone 2	Zone 3	Zone 4	Die zones
HD5050EA					
All 3 screw geometries					
180 °C	130	155	165	180	180 °C
200 °C	140	170	185	200	200 °C
220 °C	150	185	205	220	220 °C
HD6007S					
Tapered (TA)					
180 °C	150	170	170	180	180 °C
200 °C	150	180	185	200	200 °C
220 °C	150	185	205	220	220 °C
Stepped (ST)					
180 °C	130	155	165	180	180 °C
200 °C	140	170	185	200	200 °C
220 °C	150	185	205	220	220 °C
Barrier flighted (BA)					
180 °C	140	165	165	180	180 °C
200 °C	140	170	185	200	200 °C
220 °C	150	185	205	220	220 °C
HD5411EA					
Tapered (TA)					
180 °C	100	130	165	180	180 °C
200 °C	100	130	185	200	200 °C
220 °C	100	130	205	220	220 °C
Stepped (ST)					
180 °C	85	130	165	180	180 °C
200 °C	85	130	185	200	200 °C
220 °C	100	130	205	220	220 °C
Barrier flighted (BF)					
180 °C	180	180	180	180	180 °C
200 °C	180	180	185	200	200 °C
220 °C	180	180	205	220	220 °C

3. Experimental

3.1. Equipment and experimental procedure

Experiments were carried out using a 63.5 mm diameter single screw extruder (Davis standard BC60) which operated with a flood feeding system, air cooling and set temperatures along the barrel controlled with Davis Standard “Dual-Therm” temperature controllers. Three extruder screws, representative of those typically used in the polymer industry, were used throughout the experiments all with a length to diameter ratio of 24:1. Schematic representations of the screw designs are shown in Fig. 1. These designs were selected to study the role of geometry on the melting performance in single screw extrusion. The free volume (FV) of each screw was defined as the free space used to process material in the extruder. These values were determined empirically using a volume displacement method.

Experiments were performed at a range of extruder screw speeds from 10 to 90 rpm in steps of 20 rpm, and sufficient time was allowed for conditions to stabilise at each screw speed before data were recorded. Three set temperature conditions were used for each material and are detailed in Table 2. Whenever possible the same set temperatures were used for each of the three polymers and three extruder screw geometries. However, where this was not possible (for example because of excessive extruder torque or irregular solids conveying) set temperatures were adjusted to maintain a stable extrusion

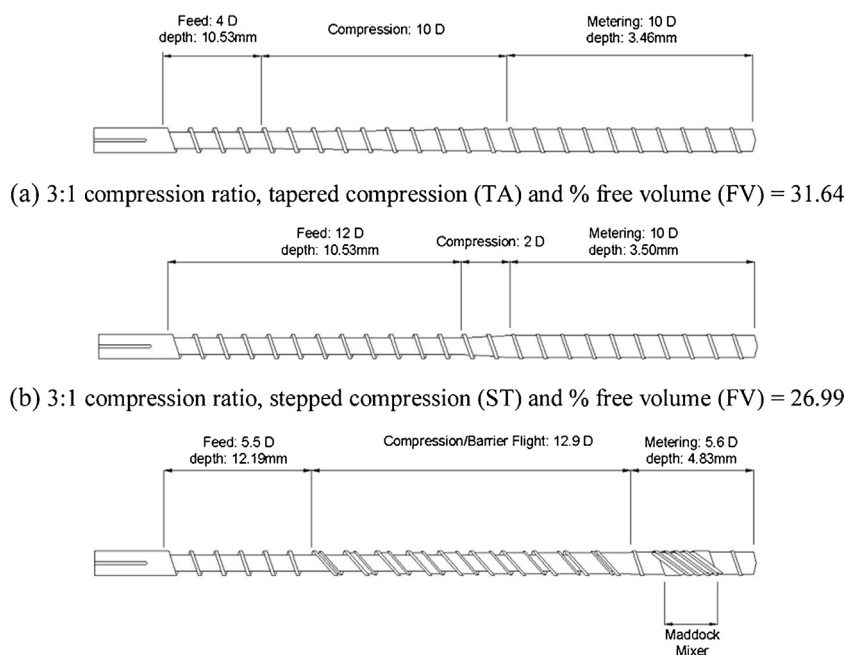


Fig. 1 – Extruder screw geometries used.

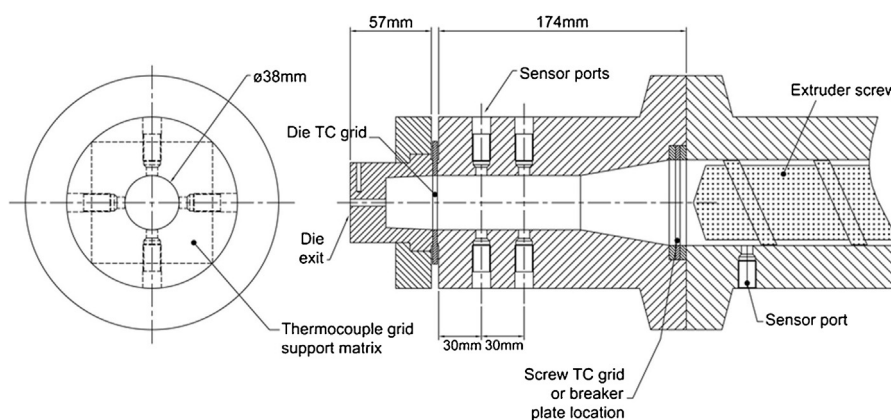


Fig. 2 – Instrumented extruder die showing location of thermocouple grid at die entrance.

process. Most notably, highest temperatures were required for HM5411EA with the barrier flighted screw, because the design of this screw requires a proportion of the polymer to be sufficiently molten to flow over the barrier flight at the start of the melting zone.

In-process monitoring techniques were used to assess the extrusion process using an instrumented die adaptor (internal diameter 38 mm) downstream of the screw and prior to the entrance of a 6 mm diameter rod die. All measurements were made at a frequency of 10 Hz using software developed in-house. A schematic diagram of this measurement region is shown in Fig. 2.

In the adaptor, a wall thermocouple (3 mm diameter J-Type) and an insulated J-Type thermocouple of 0.5 mm diameter protruding 1.0 mm into the melt were fitted. This enabled measurement of two melt temperatures values; one representing the temperature of the wall and another representing the temperature of the melt close to the wall. A thermocouple mesh, previously described by the authors (Brown et al., 2004), was placed prior to the extruder die which in conjunction with the thermocouples described above generated detailed information concerning melt temperature across the flow path. The design of the thermocouple mesh incorporated seven junctions located on a central axis across the flow

channel in a non-symmetrical spacing. The thermocouple grid allowed 2D profiles of melt temperature flowing through the die to be measured in real time, enabling characterisation of the thermal dynamics of the extrusion process. Temperature measurements were examined at each position over 30 s and 5 s periods at 90 rpm, providing 14 data points about the central axis plus and averaged output from wall and isolated wall thermocouples. In total, 15 data points were used to construct radial melt temperatures to collect information relating to short-term melt temperature changes. Construction of the thermocouple mesh sensor is shown schematically in Fig. 3.

A melt pressure transducer (Dynisco PT422A) was fitted in the die adaptor in order to examine pressure variation and its relationship to melt temperature, providing information regarding fluctuations caused by melting instabilities. Real-time quantification of energy consumption was monitored using a 3-phase unbalanced loads energy metre (Hioki 3169) connected to the 3-phase power supply of the extruder. This measured total energy consumption of the extrusion process, including consumption by the motor, heaters and cooling fans. As a result, the relationships between set process conditions, thermal dynamics, melt pressure and energy consumption could be explored.

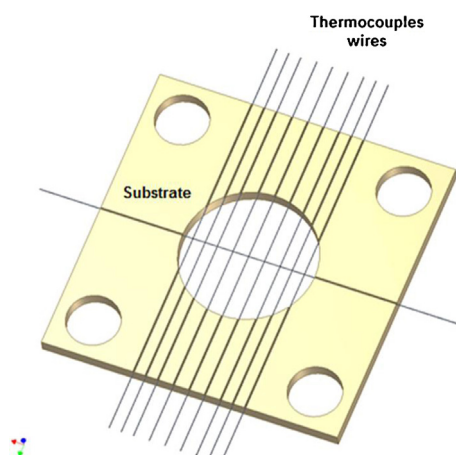


Fig. 3 – Construction of the thermocouple mesh sensor.

3.2. Material characterisation

Thermal analysis of the HDPEs was performed using a Differential Scanning Calorimeter (DSC Q20, TA instruments). DSC analysis was performed on 5–10 mg samples by heating over the temperature range from ambient to 200 °C at 10 °C/min heating rate under a nitrogen atmosphere, followed by controlled cooling at 10 °C/min to ambient. The rheological behaviour of the HDPEs was studied using a Rosand RH10 twin bore capillary rheometer over a shear rate range of 10–1000 s^{−1} in 8 stages. The capillary dies had 180° entrance angles and dimensions of 32 mm × 2 mm diameter and 0 mm × 2 mm diameter. Two repeated tests were performed for all materials at rheometer set temperatures of 180 °C, 200 °C and 220 °C.

4. Results and discussion

4.1. Thermal analysis and rheological measurements

The melt peak temperature (melting point), enthalpy of melting and degree of crystallinity, considering 290 J/g for a 100% crystalline polyethylene (Crompton, 2006) were calculated using DSC. Thermal measurements are summarised in Table 3 together with manufacturer quoted solid density.

Physical properties of HDPE, such as strength, stiffness, thermal properties and rheology, are highly affected by molecular weight (Mw) and its distribution (MWD) (Cogswell, 1996). From the data previously shown in Table 1, HM5411EA would be expected to require more energy to process compared to HD5050EA and HD6007S due to the higher values of Mw and its distribution reflected by the lower value of melt flow index (MFI). The degree of crystallinity has relatively little effect on processability, as any crystalline structure is destroyed in the melt phase (Cogswell, 1996). However, in terms of energy consumption crystallinity can influence the energy required for melting. Higher densities of HDPE result from the higher crystalline fraction (Hoffman and McKinley, 1985) as shown in Table 3.

A comparison of shear viscosity for each polymer is shown in Fig. 4 at three set temperatures. Viscosity is shown to decrease with increasing temperature and decreasing molecular weight as could be expected. In the shear rate region typically associated with flow in extruder screw channels, the shear viscosity was clearly ordered as follows: HD5411 > HD6007 > HD5050. However, at higher shear strain rates HD6007 exhibited greater shear thinning than HD5050,

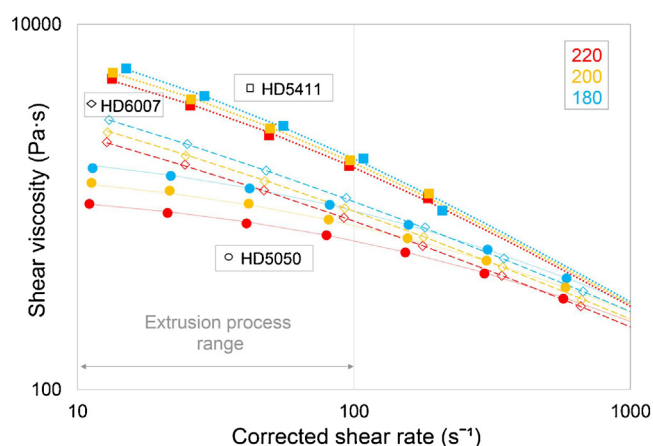


Fig. 4 – Shear viscosity measured using a twin bore capillary rheometer (lines indicate fit of Carreau–Yasuda model).

probably as a result of the higher molecular weight distribution of this grade.

A Carreau–Yasuda model (Carreau, 1968; Yasuda, 1979) was fitted to the measured rheological data for each material and set temperature, as shown in Fig. 4. A good agreement between the model and experimental data was found. Temperature dependence for each polymer was also modelled using exponential temperature dependence at reference temperature of 180 °C.

The exponential temperature dependence and Carreau–Yasuda model are given by:

$$f(T) = e^{-b(T - T_r)} \quad (1)$$

$$\eta(\dot{\gamma}, T) = \frac{A f(T)}{[1 + (r \dot{\gamma} f(T))^a]^{(1-n)/a}} \quad (2)$$

This modelled data was then used to calculate bulk viscosity inside the metering section of the extruder screw, for each polymer, set temperature, screw geometry and screw rotation speed. Shear rate ($\dot{\gamma}$) in the screw channel at the end of the metering section (Giles et al., 2005) was calculated from:

$$\dot{\gamma} = \frac{\pi \times D \times N}{60 \times h} (s - 1) \quad (3)$$

where D is the screw diameter in mm, N is the screw speed in rpm and h is the channel depth in mm.

Measured temperatures from the thermocouple mesh junctions, averaged over a period of 1 min (Kelly et al., 2006) coupled with the above equation and modelled rheological data were used to predict melt viscosity at the end of the extruder screw at each experimental condition. An example is shown in Table 4.

These calculations in conjunction with temperatures measured using the thermocouple mesh and real-time quantification of energy consumption enabled the exploration of the effect of shear viscosity on the measured melt temperatures and process energy demand.

4.2. Extrusion measurement

Extrusion data are presented to show the effects of screw geometry, set machine temperatures and material properties (Mw, melt viscosity) on melt quality (measured in terms of temperature and temperature homogeneity), pressure vari-

Table 3 – Thermal data for three grades of HDPE.

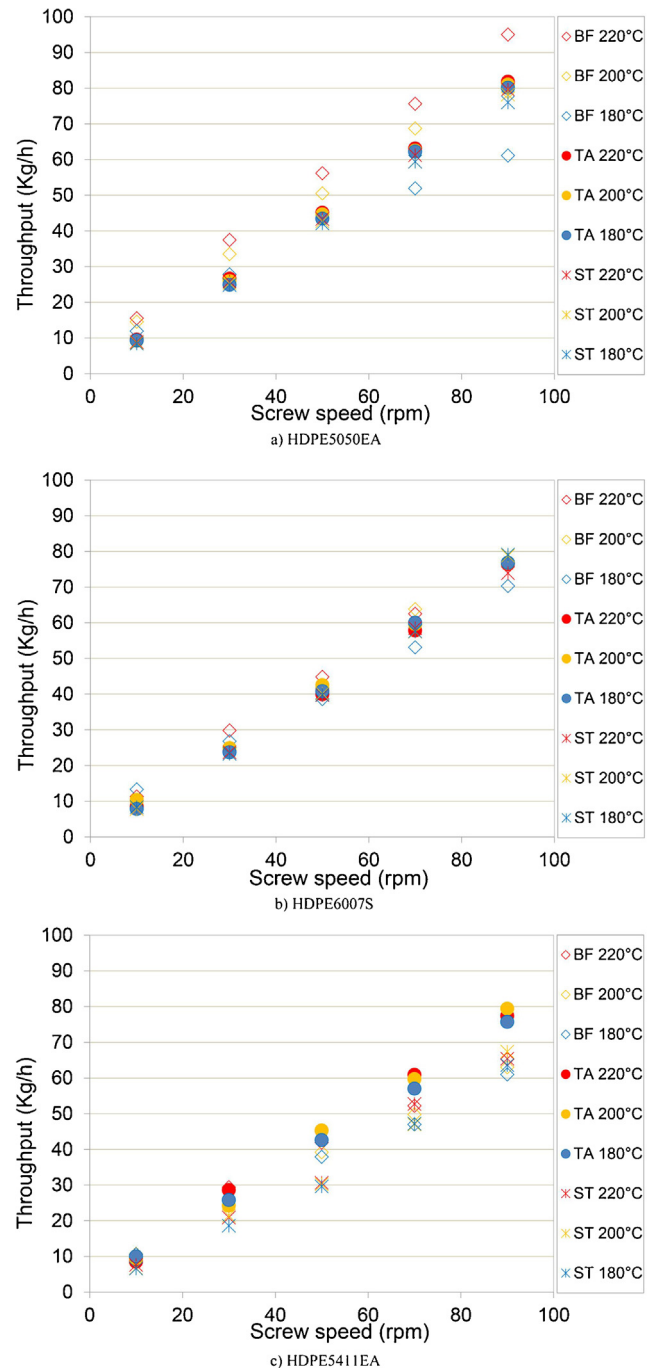
	Melt peak temperature (°C)	Enthalpy (J/g)	Crystallinity (%)	Density (kg/m ³)
HD5050EA	130.82	139.03	47.94	950
HD6007S	133.75	175.90	60.65	962
HM5411EA	131.32	133.90	46.17	952

ation and total process energy consumption. Fig. 5 displays extruder performance in terms of throughput for all grades of HDPE by examining the effects of screw speed, extruder set temperature and screw geometry. This highlights the dependence of productivity on melt viscosity; throughputs were higher for HD5050EA compared to HM5411EA, reflecting the lower molecular weight of the former and its effect on shear viscosity, as previously shown in Fig. 4.

Set temperature appeared to have a major effect on throughput for the barrier flighted screw processing HD5050EA as seen in Fig. 5a. At the same set temperature profile of 220 °C, the barrier flighted screw produced higher throughputs than the two single flighted screws. The free volume of the barrier flighted screw is significantly greater than the free volume of single flighted screws and at this temperature, the channel was more readily filled due to the lower viscosity of the polymer. At 180 °C, however, a non-linear behaviour and a lower throughput was observed. Throughput is heavily dependent upon the polymer's thermal and frictional properties and due to their design, barrier flighted screws require more work input to melting the polymer as it is forced to flow over extra flights in the barrier and mixer sections of the screw. The extra work required at lower temperature appears here to inhibit the total throughput, especially at higher speeds where achieving melting is more challenging. This could also explain the lower throughputs observed for the highest viscosity grade HM5411EA (Fig. 5c) despite the careful selection of the barrel set temperature profiles (Table 2).

Extruder throughput for the medium grade HD6007S was found to be relatively unaffected by screw geometry and set temperatures as shown in Fig. 5b, which could be explained by optimised selection of barrel set temperature profiles (Table 2).

A detailed examination of the thermal dynamics of the extrusion process was carried out using the thermocouple grid located in the entrance of the extruder die which enabled measurements of radial melt temperature over a period of 30 s. The effect of screw speed on dynamic melt temperatures for the medium viscosity grade HD6007S measured with each screw geometry at a set temperature of 200 °C is displayed in Fig. 6. For both single flighted screws, short-term melt temperature changes were observed at screw speeds above 30 rpm and these were greatest at radial positions of 4.5 and 11 mm from the centre of the flow. Temporal variations of temperature at each junction across the flow path, however, were not observed for the barrier flighted screw (Fig. 6c). This is likely to be as a result of improved melting previously described by the authors (Brown et al., 2004) with the use of thermocouple

**Fig. 5 – Measured extruder throughput for each HDPE.****Table 4 – Melt viscosity at the end of the extruder screw.**

HD5050EA Tapered 200 °C	<i>h</i> (mm)	$\dot{\gamma}$ (s ⁻¹)	Mesh (°C)	<i>f</i> (T)	η (Pa s)
<i>rpm</i>					
10	3.46	9.54	231.00	0.479	917.01
30	3.46	28.62	231.89	0.473	776.10
50	3.46	47.70	228.84	0.494	725.50
70	3.46	66.78	226.26	0.513	688.01
90	3.46	85.87	223.82	0.531	658.85

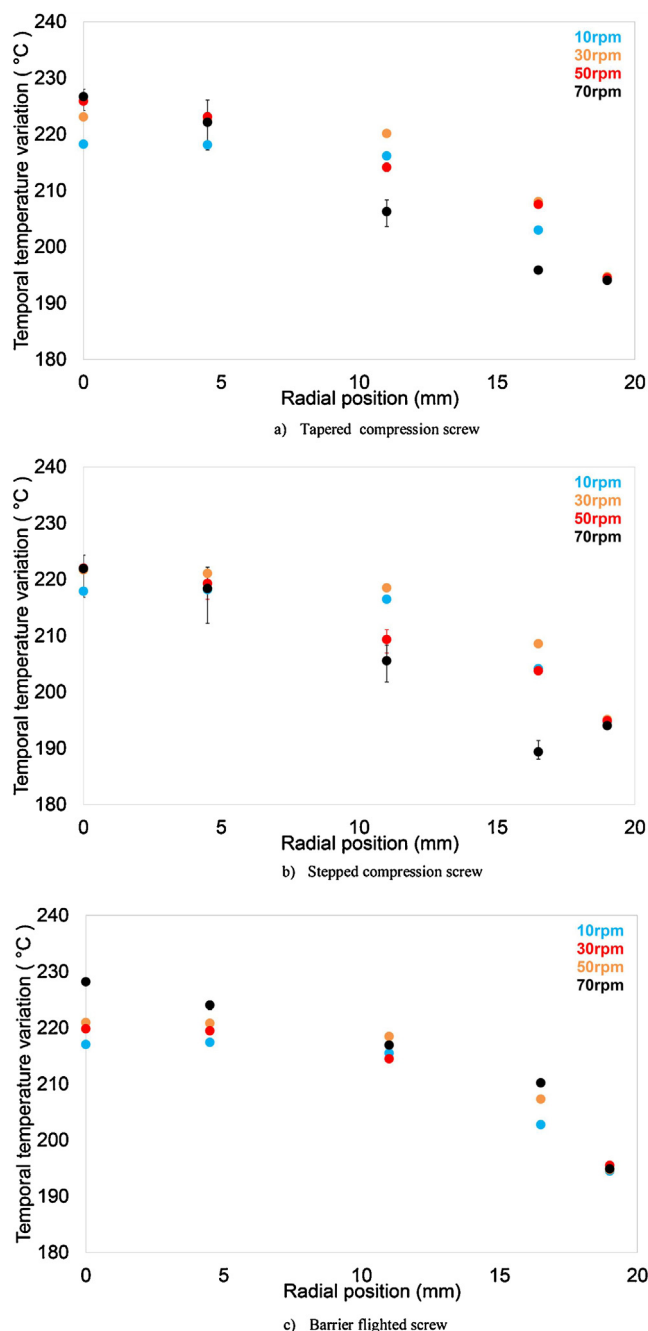


Fig. 6 – Effect of screw speed on radial melt temperature variations for HD6007S at 200 °C over a 30 s period (error bars denote maximum range of temperature during the measurement period).

meshes at the same conditions for the lower viscosity grade HD5050EA.

Variations of melt temperature were observed at 11 mm from the centre of the flow above 50 and 70 rpm for single flighted screws. Fig. 7 shows melt temperature changes at this position and a screw speed of 70 rpm at the same conditions over a 30 s period to reflect again the melt temperature consistency achieved for the barrier flighted screw compared to single flighted screws. Melt temperature was less consistent as screw speed increased, especially for single flighted screws; therefore the effect of Mw on thermal dynamics is compared directly at 90 rpm for all grades of HDPE at 200 °C using three different screws over a 5 s period and shown in Fig. 8.

Previous work has established that radial melt temperatures were symmetrical (Brown et al., 2004) so measured melt

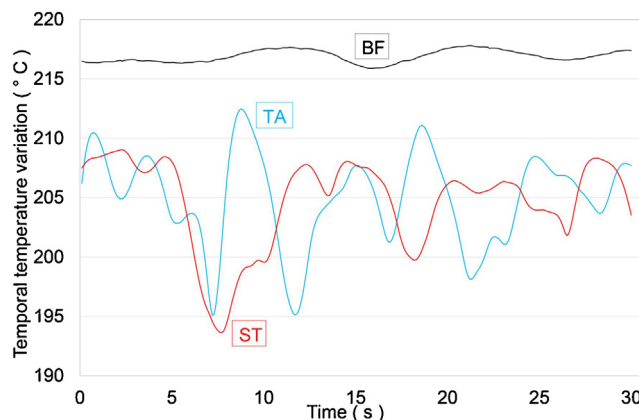
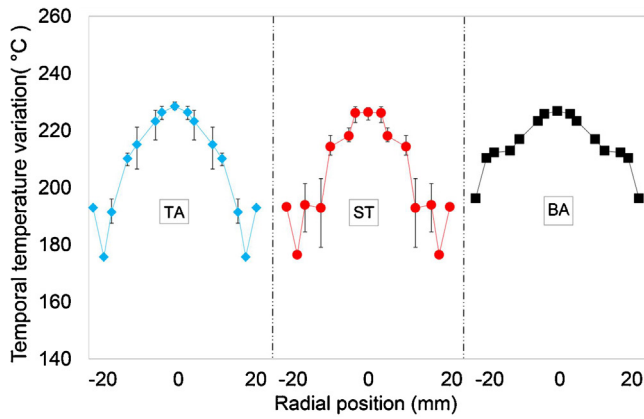


Fig. 7 – Variation of melt temperature for HD6007S at 200 °C over a 30 s period at 11 mm from the centre of the flow and screw speed of 70 rpm.

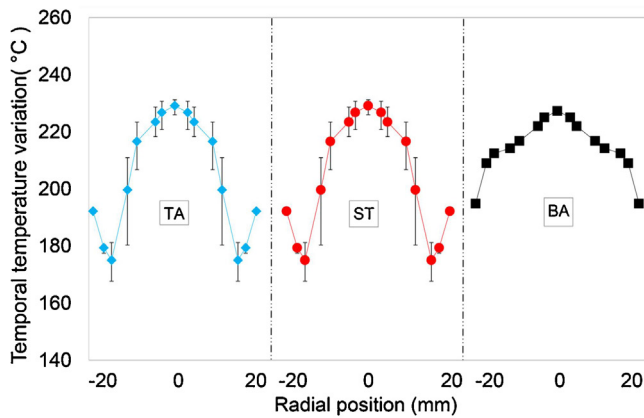
temperatures at each junction were mirrored about the central axis at 90 rpm. It can be observed for single flighted screws that the range of temperature variation at each junction significantly increased with increasing HDPE viscosity. The largest ranges of fluctuations were measured for the highest viscosity grade (HM5411EA). A temperature difference of up to 65 °C was recorded at 8.8 mm from the centre of the flow for the tapered compression screw during the measurement period (Fig. 8c). However, melt temperature variations were smaller with the barrier flighted screw for all grades of HDPE at the same conditions, as seen in Fig. 8a–c. It was noticed that for HD5411EA and the barrier flighted screw (Fig. 8c), the melt temperature increased across the flow volume having a peak temperature in the centre of around 240 °C which could be explained by the highest barrel set temperature profiles being required for HM5411EA in addition to increased viscous energy dissipation via shearing. These results highlight the dependence of melt viscosity on molecular weight and its effect on the thermal dynamics of the extrusion process; the high viscosity of this grade of HDPE leading to a high dependence of homogeneity on screw geometry.

Magnitude and levels of fluctuation in measured melt temperature are plotted against melt viscosity in Figs. 9 and 10 at all screw speeds and a set temperature of 200 °C. Fig. 9 shows that melt viscosity had a pronounced effect on measured temperature, which increased with increasing melt viscosity. This can be explained by the higher levels of viscous shear generated during extrusion of higher viscosity polymer. Interestingly, for both single flighted screws the measured temperature initially increased with increasing screw rotation speed (as could be expected to due viscous shear heating) but then decreased above a critical screw speed, typically 30 or 50 rpm. This reflects a point at which the melting mechanism began to break down when there was insufficient time for the volume of polymer within the screw channel to be melted homogeneously. For the barrier flighted screw this critical point was not reached and measured melt temperature continued to rise with increasing screw speed, reflecting the improved melting action of the barrier screw.

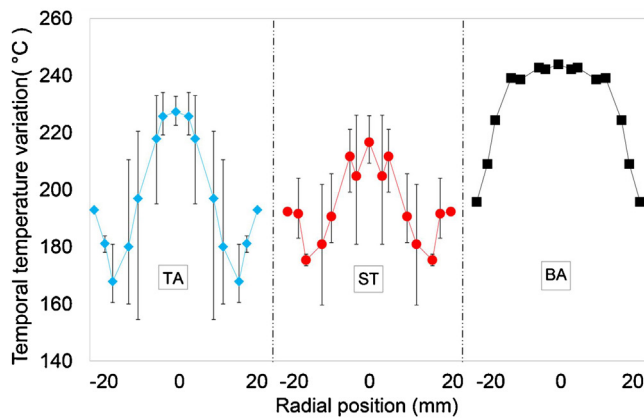
Fig. 10 shows a corresponding plot of melt temperature fluctuation over a period of 1 min, versus melt viscosity, at the same set conditions as shown in Fig. 9. The viscosity of the different HDPE grades had a less significant effect on temperature variation (quantified by standard deviation), which ranged from 0.01 to 8.3 °C. The lowest viscosity grade of HDPE



a) HD5050EA



b) HD6007S



c) HD5411EA

Fig. 8 – Effect of Mw on dynamic melt temperatures, all grades of HDPE, 200 °C, measured over 5 s at 90 rpm.

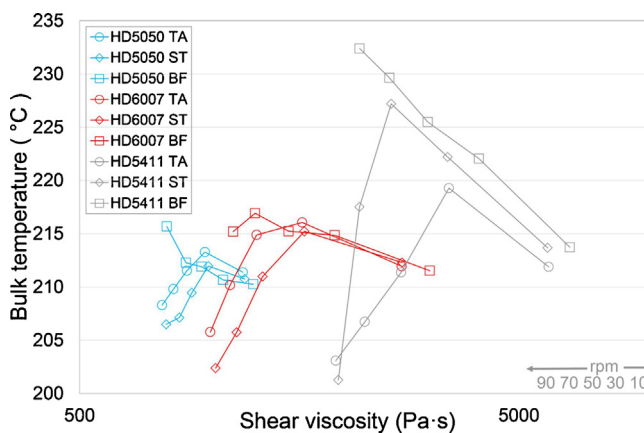


Fig. 9 – Bulk temperature measurements at 200 °C.

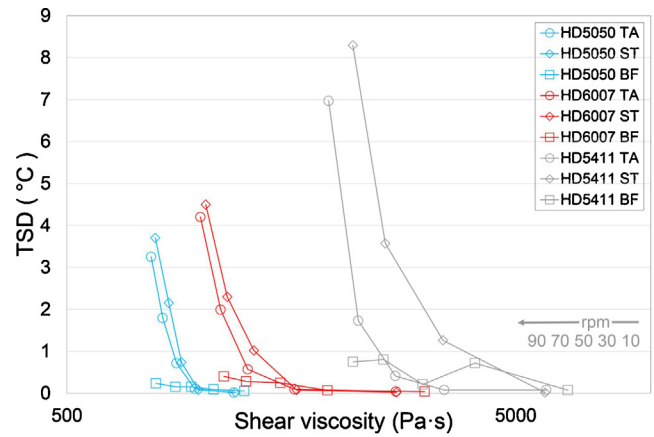
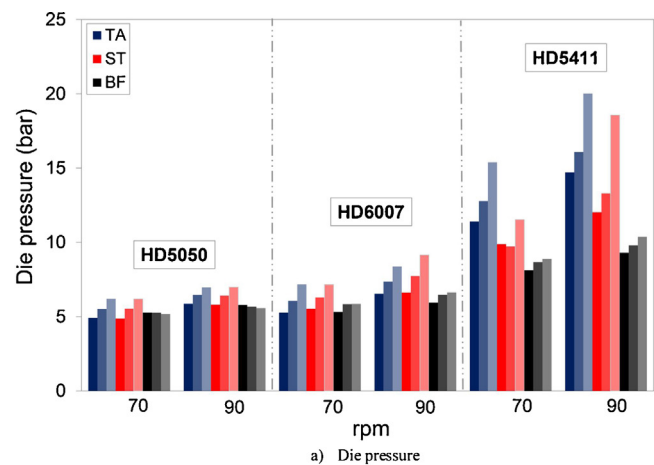


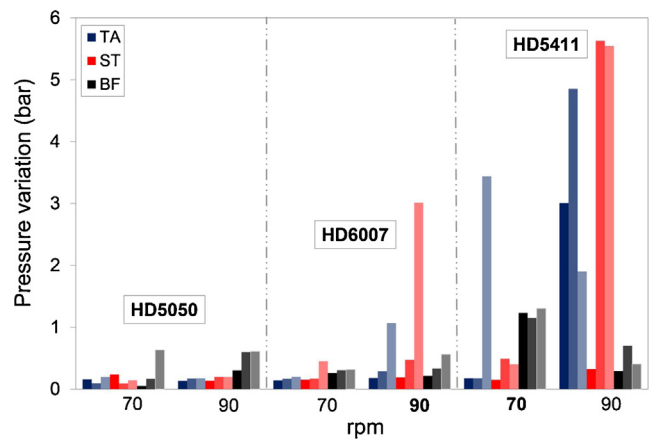
Fig. 10 – Standard deviation of temperature measurements at 200 °C.

exhibited fluctuations between 0.01 and 3.7 °C compared to 0.01–8.3 °C for the highest viscosity grade. The most significant observation related to a large increase in the levels of fluctuation above the critical screw speed described above, for single flighted screws. This suggests that a break down in the effectiveness of the melting process is associated with a corresponding decrease in melt homogeneity.

Measured die pressure and pressure variations are displayed in Fig. 11 at the highest set screw speeds of 70 and 90 rpm. Die pressures increased as set temperatures decreased and were lower for barrier flighted screw for all grades of HDPE



a) Die pressure



b) Pressure variation

Fig. 11 – Die pressure and melt pressure variation for all grades of HDPE (dark colours represent 220 °C, medium 200 °C and light 180 °C).

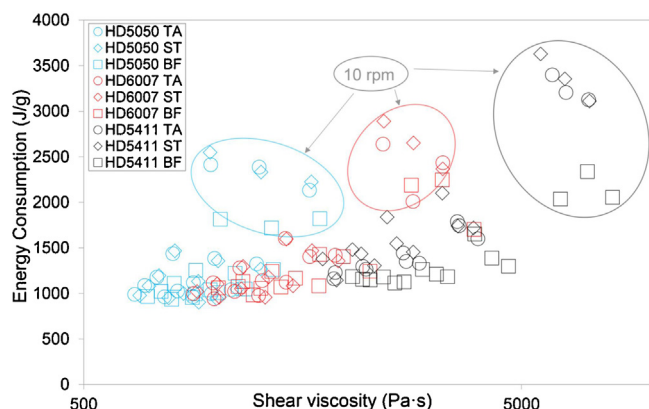


Fig. 12 – Effect of shear viscosity on process energy demand, representing three grades of HDPE for three screw geometries and set temperatures.

(Fig. 11a). High die pressures were observed for HM5411EA which were strongly dependent upon screw geometry and set extruder temperatures. Despite the higher pressures measured for HD5411EA, lower throughputs were produced, as shown earlier in Fig. 5, reflecting the poorer processing capability of these screw geometries for high molecular weight of HDPE. This could also be explained by higher levels of pressure variation seen in Fig. 11b, which corresponded to the higher levels of temperature fluctuation shown in Fig. 10.

The effect of shear viscosity on extrusion process energy demand is shown in Fig. 12. Specific energy consumption was defined as the energy consumption divided by mass throughput, calculated over a period of 1 min. Shear viscosity is plotted on the x-axis and reduces as screw speed increases from 10 rpm to 90 rpm. A large variation in specific energy consumption was observed, between 800 and 3700 J/g, dependent upon polymer grade, screw geometry, set temperature and screw speed. Fig. 12 shows a clear dependence of energy consumption on melt viscosity, across all three HDPE grades and set temperatures. In general, energy consumption increased with increasing melt viscosity due to the dependence of viscous shear on melt viscosity. Specific energy consumption was generally found to be lower for the barrier flighted screw corresponding to the improved melting performance of this screw previously discussed.

Highest energy consumption was observed for all grades of HDPE at the lowest screw rotation speed of 10 rpm. A previous study by the authors (Kelly et al., 2006) noted that conduction was the dominant form of heat generation at low screw speeds in contrast to viscous shearing at higher speeds. These results suggest that melting predominantly by conduction is less efficient and indicates that the extruder should be run at medium to high screw speeds to improve specific energy consumption. Interestingly, at screw speeds above 10 rpm the measured specific energy consumption for all HDPEs and set conditions followed a relatively linear dependence upon melt viscosity, irrespective of set temperature and screw geometry. This finding suggests that melt viscosity could be used as a simple method of predicting or benchmarking specific energy consumption, for a particular grade of polymer such as HDPE.

While it is recognised that melt quality and associated product functionality is the first priority in extrusion, the data indicate an acceptable process window within which melt quality is high. By judicious selection of extruder screw geometry, set process temperature conditions and appropriate screw speeds for a particular material type and grade, energy

efficiency can be optimised without any reduction in melt quality. For the polymers and extruder used in this study, low screw rotation speeds were found to consume higher levels of specific energy, whereas for single flighted screws intermediate screw rotation speeds produced the best balance between melt quality and energy consumption. A barrier flighted screw with spiral mixer provided the best melt quality over a greater screw speed range.

5. Conclusions

The effect of HDPE rheology and set processing conditions on the thermal efficiency of the single screw extrusion process was studied using a highly instrumented extruder. Results reflected high levels of variation in radial melt temperatures across the die flow path, dependent on screw geometry, screw rotation speed, set temperature and polymer viscosity. Single flighted extruder screws exhibited poorer temperature homogeneity and larger fluctuations than a barrier flighted screw with a spiral mixer. Bulk temperature and the magnitude of temperature fluctuations increased with increasing melt viscosity for the three HDPEs studied. Specific energy consumption was found to be predominantly dependent upon polymer melt viscosity and its effect on the efficiency of the extrusion process and melt quality was clearly demonstrated. These results highlight the importance of careful selection of processing conditions and extruder screw geometry on melt homogeneity and process efficiency.

Acknowledgements

This work was funded through an inter-disciplinary research programme (EP/G059330/1) by the Engineering and Physical Sciences Research Council of the UK. The technical assistance of Steve Brook, Ken Howell, Glen Thomson and John Wyborn at the University of Bradford are gratefully acknowledged.

References

- Abeykoon, C., Martin, P.J., Kelly, A.L., Brown, E.C., 2012. A review and evaluation of melt temperature sensors for polymer extrusion. *Sens. Actuators A* 182, 16–27.
- Agassant, J.F., Villemaire, J.P., 1998. Rheology for polymer processing: an overview of the present knowledge and some open problems. *Makromol. Chem. Macromol. Symp.* 22, 39–57.
- Brown, E.C., Kelly, A.L., Coates, P.D., 2004. Melt temperature field measurement in single screw extrusion using thermocouple meshes. *Rev. Sci. Instrum.* 75, 4742–4748.
- Cantor, K.M., 2010. Analyzing extruder energy consumption. In: *SPE ANTEC Tech. Papers*, pp. 603–609.
- Carreau, P.J., 1968. *Rheological Equations from Molecular Network Theories*. University of Wisconsin, Madison (Ph.D. thesis).
- Cogswell, F.N., 1996. *Polymer Melt Rheology*. Woodhead Publishing, Cambridge, England.
- Craig, R.F., Rakes, J.L., Solop, Eli., 1968. New trends in thermoplastic sheet processing, extruding and thermoforming extra high molecular weight high density polyethylene. In: *SPE ANTEC Tech. Papers*, pp. 25–34.
- Crompton, T.R., 2006. *Polymer Reference Book*. Rapra Technology Limited, Shrewsbury, UK.
- Giles, H.F., Wagner, J.R., Mount, E.M., 2005. *Extrusion: The Definitive Processing Guide and Handbook*, 1st ed. William Andrew Publishing, New York.
- Hoffman, D.M., McKinley, B.M., 1985. Crystallinity as a selection criterion for engineering properties of high density polyethylene. *Polym. Eng. Sci.* 25, 562–569.

- Kelly, A.L., Brown, E.C., Coates, P.D., 2006. The effect of screw geometry on melt temperature profile in single screw extrusion. *Polym. Eng. Sci.* 46, 1706–1714.
- Kelly, A.L., Vera-Sorrorche, J., Brown, E.C., Coates, P.D., 2012. Improving thermal efficiency of single screw extrusion. In: *SPE ANTEC Tech. Papers*, pp. 1080–1088.
- Krishnaswamy, R.K., Rohlfing, D.C., 2004. Extrusion of broad-molecular weight distribution polyethylenes. *Polym. Eng. Sci.* 44, 2266–2273.
- Lee, C.D., Wheeler, N.C., 1991. A study on the performance of barrier-screw extruders. *Polym. Eng. Sci.* 31, 831–841.
- Plastics – the Facts, 2012. An Analysis of European Plastics Production, Demand and Waste Data for 2011. *PlasticsEurope*.
- Rauwendaal, C., 1990. *Polymer Extrusion*, 2nd ed. Hanser, Munich.
- Steward, E., 2002. Barriers screws, their history and their function. In: *SPE ANTEC Tech. Papers*, pp. 69–73.
- Vera-Sorrorche, J., Kelly, A.L., Brown, E.C., Coates, P.D., Karnachi, N., Harkin-Jones, E., Li, K., Deng, J., 2012. Thermal optimisation of polymer extrusion using in-process monitoring techniques. *Appl. Therm. Eng.* 53, 405–413.
- Yasuda, K., 1979. Investigation of the analogies between viscometric and linear viscoelastic properties of polystyrene fluids. MIT, Cambridge (Ph.D. thesis).